



Baseline Testing of Ultracapacitors for the Next Generation Launch Technology (NGLT) Project

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Page 7, “Concluding Remarks”: The first and second sentences have been changed to read “The Ballard Nexa proton exchange membrane (PEM) fuel cell has been tested very successfully with symmetric ultracapacitor energy storage. The primary focus of this report is to present the test results of a symmetric ultracapacitor energy storage system.”

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Summary

The NASA John H. Glenn Research Center initiated baseline testing of ultracapacitors for the Next Generation Launch Technology (NGLT) project to obtain empirical data for determining the feasibility of using ultracapacitors for the project. There are large transient loads associated with NGLT that require either a very large primary energy source or an energy storage system. The primary power source used for these tests is a proton exchange membrane (PEM) fuel cell. The energy storage system can consist of devices such as batteries, flywheels, or ultracapacitors. Ultracapacitors were used for these tests.

Ultracapacitors are ideal for applications such as NGLT where long life, maintenance-free operation, and excellent low-temperature performance is essential. State-of-the-art symmetric ultracapacitors were used for these tests. The ultracapacitors were interconnected in an innovative configuration to minimize interconnection impedance. PEM fuel cells provide excellent energy density, but not good power density. Ultracapacitors provide excellent power density, but not good energy density. The combination of PEM fuel cells and ultracapacitors provides a power source with excellent energy density and power density. The life of PEM fuel cells is shortened significantly by large transient loads. Ultracapacitors used in conjunction with PEM fuel cells reduce the transient loads applied to the fuel cell, and thus appreciably improves its life. PEM fuel cells were tested with and without ultracapacitors, to determine the benefits of ultracapacitors. The report concludes that the implementation of symmetric ultracapacitors in the NGLT power system can provide significant improvements in power system performance and reliability.

Introduction

The NASA Glenn Research Center has a wealth of experience in ultracapacitor technology through the Hybrid Power Management (HPM) Program. The Avionics, Power and Communications Branch of the Engineering Development Division initiated the HPM Program for the Technology Transfer & Partnership Office. HPM is the innovative integration of diverse state-of-the-art power devices in an optimal configuration for space and terrestrial applications. The appropriate application and control of the various power devices significantly improves overall system performance and efficiency. The advanced power devices include ultracapacitors and fuel cells. HPM applications have extremely wide potential and include power generation, transportation systems, biotechnology systems, and space power systems. HPM has the potential to significantly alleviate global energy concerns, improve the environment, and stimulate the economy.

One of the unique power devices being utilized by HPM for energy storage is the ultracapacitor. A capacitor is an electrical energy storage device consisting of two or more conducting electrodes separated from one another by an insulating dielectric. An ultracapacitor is an electrochemical energy storage device, which has extremely high volumetric capacitance energy due to high surface area electrodes, and very small electrode separation. Ultracapacitors have many advantages over batteries:

(1) Batteries can only be charged and discharged hundreds of times, and then must be replaced. Ultracapacitors can be charged and discharged over 1 million times. The long cycle life of ultracapacitors greatly improves system reliability and reduces life-of-system costs.

(2) Long ultracapacitor life significantly reduces environmental impact, as ultracapacitors will probably never need to be replaced and disposed of in most applications.

(3) The environmentally safe components of ultracapacitors greatly reduce disposal concerns.

(4) High ultracapacitor power density provides high power during surges and the ability to absorb high power during recharging. Ultracapacitors are extremely efficient in capturing recharging energy.

(5) Ultracapacitors are extremely rugged, reliable, and maintenance free.

(6) Ultracapacitors have excellent low-temperature characteristics.

(7) Ultracapacitors provide consistent performance over time.

(8) Ultracapacitors promote safety, as they can easily be discharged, and left indefinitely in a safe discharged state.

HPM has been successfully applied to the NASA Hybrid Electric Transit Bus (HETB) project. This is a 12.2-m (40-ft) transit bus with a unique hybrid drive. At over 17 000 kg (37 000 lb) gross weight, this is the largest vehicle to ever use ultracapacitor energy storage. The ultracapacitor technology utilized for the HETB is being applied to satellite actuation to replace unreliable hydraulic systems. The motor and control technology utilized for the HETB is being applied to flywheel dynamometer systems.

HPM has been utilized to provide power for drop tower research. HPM is being considered for space missions, such as the exploration of Mars, and deep space missions, such as the exploration of Europa.

Through the Glenn Technology Transfer & Partnership Office, HPM is being applied to power generation, transportation, safety, and biotechnology systems. Some specific examples include photovoltaic power generation, electric vehicles, and safety systems.

Testing

Objectives

Testing of the ultracapacitors was performed at Glenn. Of particular interest is the performance of an ultracapacitor bank in conjunction with a proton exchange membrane (PEM) fuel cell. In addition, an ultracapacitor bank was developed to operate at the NGLT nominal voltage level of 275 V to verify performance at that voltage level.

Hardware

The Ballard Nexa (Ballard Power Systems, Inc., Burnaby, BC, Canada) power module is a small, low maintenance and fully automated fuel cell system designed to be integrated into products for portable and back-up power markets. It is ready to integrate into a variety of products for commercial use. The Nexa power module is shown in the fuel cell laboratory in figure 1 and is described in detail in appendix A. The Nexa system is based on a PEM hydrogen, air fuel cell. The system provides up to 1200 W of unregulated dc power at a nominal output voltage of 26 Vdc. With the use of an external fuel supply, operation is continuous, limited only by the amount of fuel storage.

A bank of 20 Maxwell BCAP0010 (Maxwell Technologies, Inc., San Diego, CA) symmetric ultracapacitors was developed to provide the voltage rating required for the fuel cell. The ultracapacitor energy storage system tested in conjunction with the fuel cell is rated at 130 F and is shown in figure 2. This state-of-the-art technology not only has much longer life than conventional batteries, but also provides much higher current capacity than batteries. Ultracapacitors are maintenance free and have excellent low-temperature characteristics. The general test configuration is shown in figure 3.

A bank of 110 Maxwell BCAP0010 symmetric ultracapacitors was developed to provide the voltage rating required for the NGLT power system. The bank has a nominal voltage rating of 275 Vdc and a nominal capacitance of 23.64 F. The bank is shown in figure 4.

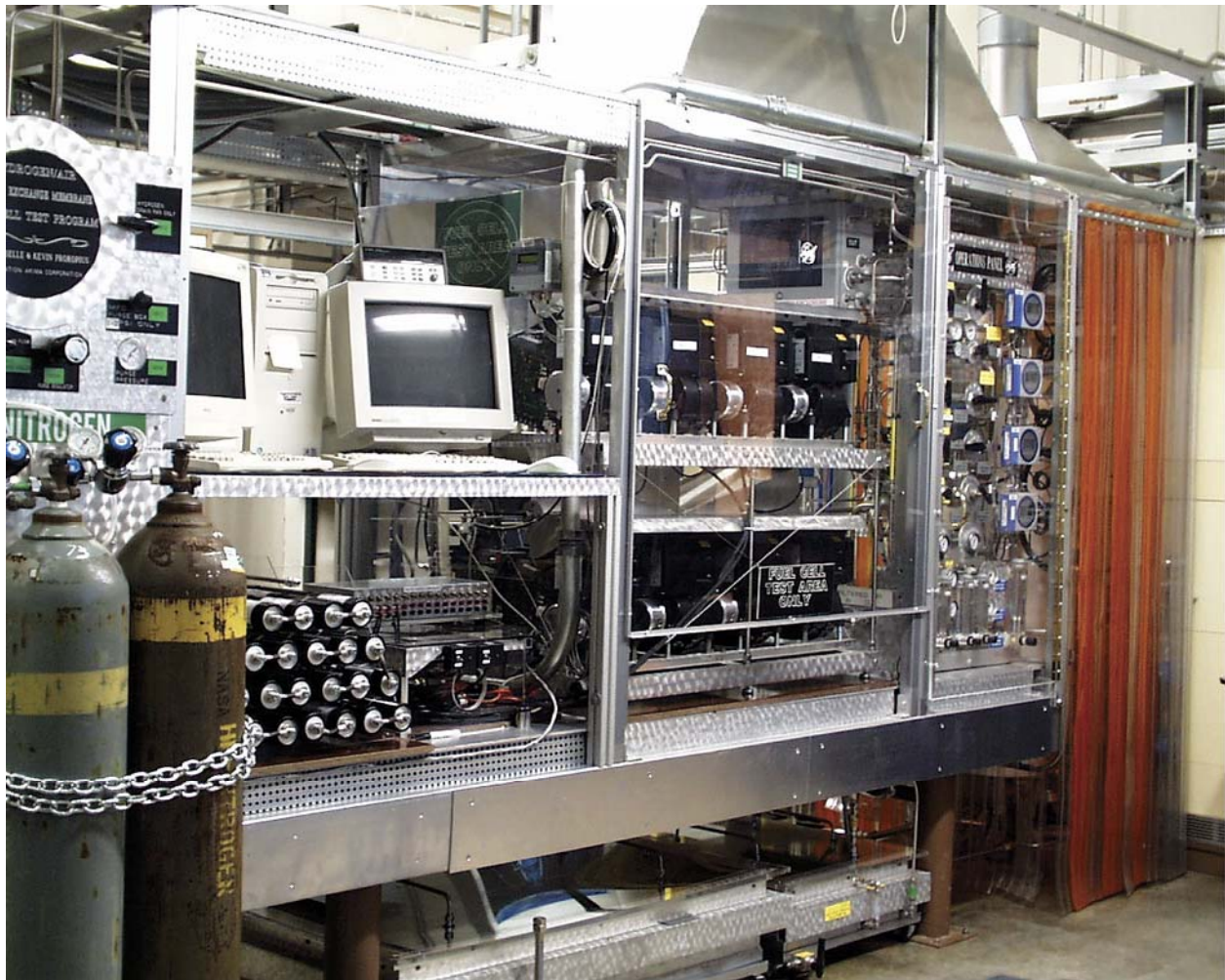


Figure 1.—Fuel cell laboratory with PEM fuel cells and ultracapacitors.

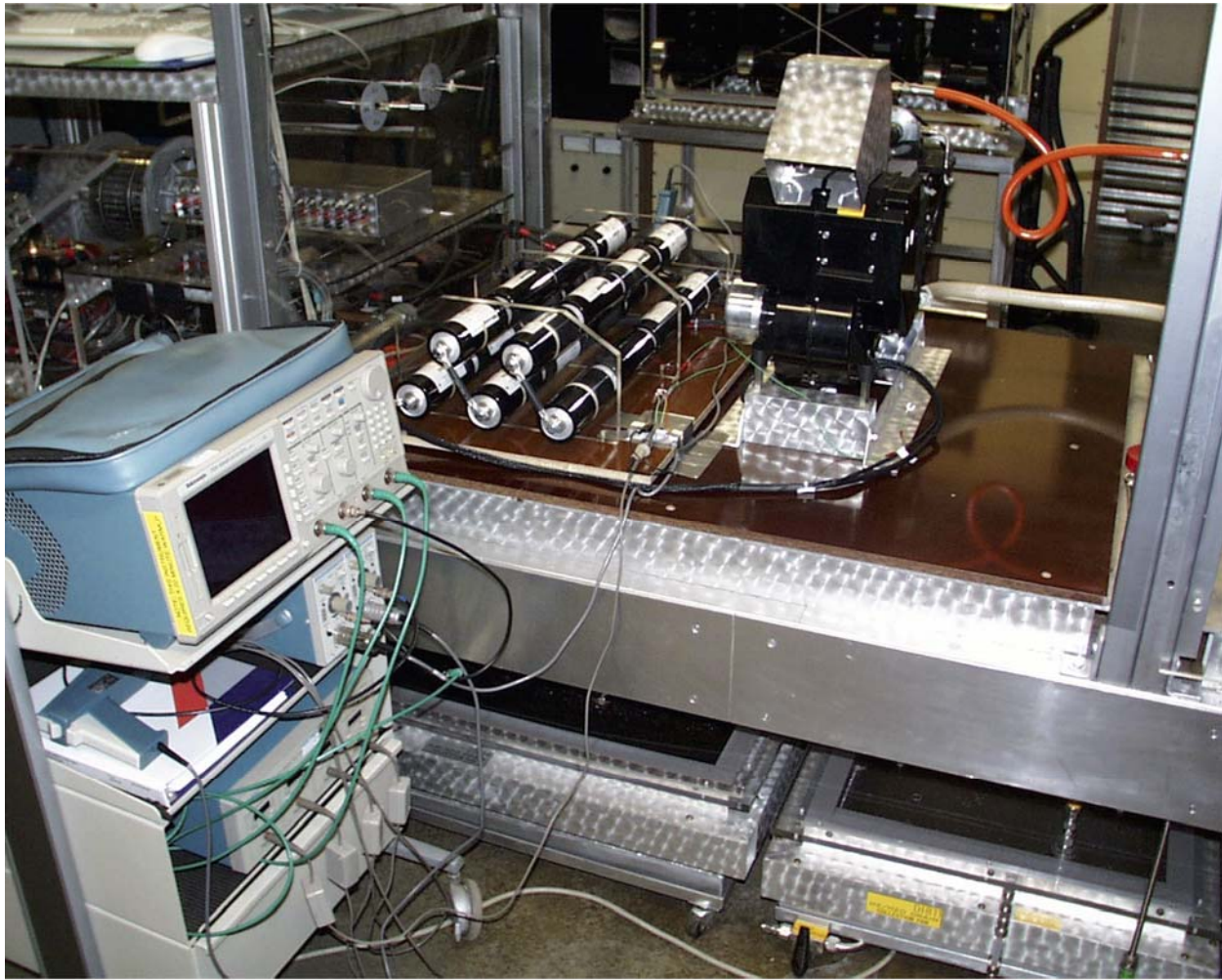


Figure 2.—Bank of 20 ultracapacitors with PEM fuel cell.

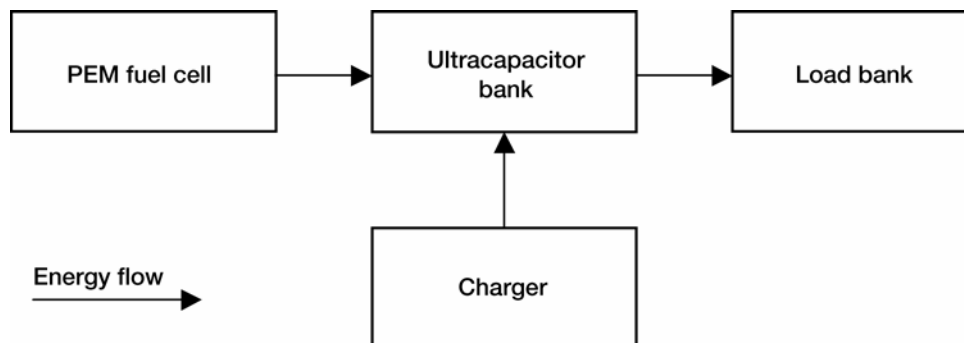


Figure 3.—Ultracapacitor-PEM fuel cell test configuration.



Figure 4.—A 275-V ultracapacitor bank consisting of 110 ultracapacitors connected in series configuration.

Instrumentation

The fuel cell, ultracapacitor bank, and load bank were instrumented to measure fuel cell performance, and ultracapacitor performance. Data from the fuel cell were obtained from the fuel cell instrumentation system and sent directly to a personal computer (PC), where the data were stored. These data included fuel cell voltage, current, and temperature. The other data were sent to a digital data acquisition system, sampled continuously, and stored on a PC. Data channels measured ultracapacitor voltage and current as well as capacitor temperature and the ambient temperature. The instrumentation configuration is described in appendix B.

Procedures

The tests described in this report were conducted at the NASA Glenn Research Center in Cleveland, Ohio. The tests were conducted in accordance with the following test matrix:

- (1) Transient test: Fuel cell with transient loads of 3 to 30 to 3 A and 3 to 50 to 3 A, with and without ultracapacitor energy storage system.
- (2) Discharge test: Bank of 20 ultracapacitors discharged into a 1- Ω load. Bank of 110 ultracapacitors discharged into a 10- Ω load.
- (3) Self-discharge test: Self-discharge bank of 110 ultracapacitors charged to 275 V over 24 hr.
- (4) Balance test: Voltage of individual ultracapacitors precharged as a bank of 110 ultracapacitors to 275 V.

Test Results

System Performance

Eight tests were conducted to determine system performance, as presented in table I: Plots have been included in appendix C for the various system tests:

- (1) Long-term transient results
- (2) Short-term transient results
- (3) Discharge results

A summary of the test results is shown in table II at the end of this section.

TABLE I.—PERFORMANCE TESTS CONDUCTED ON PEM FUEL CELL AND ULTRACAPACITOR POWER SYSTEM

Test number	Energy source	Ultracapacitor bank	Load	Test mode
1	Fuel cell	None	30 A	Transient test
2	↓	Series of 20	30 A	↓
3		None	50 A	
4		Series of 20	50 A	
5		Series of 20	1 Ω	Discharge test
6	↓	Series of 110	10 Ω	Discharge test
7		Series of 110	None	Self-discharge test
8		Series of 110	None	Balance test

Transient Test

The transient response of the fuel cell was significantly improved with the addition of a bank of ultracapacitors to the system. The fuel cell voltage without ultracapacitors dropped 21.99 percent 1 s after a 30-A load was applied. The fuel cell voltage with ultracapacitors dropped 5.50 percent 1 s after a 30-A load was applied. The fuel cell voltage without ultracapacitors dropped 36.97 percent 1 s after a 50-A load was applied. The fuel cell was only able to sustain this load for 2 s, and then it shut down because 35 A is the maximum current the fuel cell can supply continuously without ultracapacitors. The fuel cell voltage with ultracapacitors dropped 7.28 percent 1 s after a 50-A load was applied. The system with ultracapacitors was able to sustain a 50-A load continuously.

Transient response test results are presented in table II and plotted in figures 6 to 11 (appendix C).

Discharge Test

The bank of 20 ultracapacitors was charged to 43 V and discharged through a 1- Ω load to 5 V in 4.7 min. The bank of 110 ultracapacitors was charged to 275 V and discharged through a 10- Ω load to 5 V in 17.9 min.

Discharge times are given in table II and plotted in figures 12 and 13 (appendix C).

Self-Discharge Test

The self-discharge of the bank of 110 ultracapacitors was determined at no load with the ultracapacitors charged to 275 V. The bank discharged 21.43 V, or 7.8 percent, in a 24-h period. Self-discharge results are indicated in table II and plotted in figure 14 (appendix C).

Summary

An overall summary of the system testing is shown in table II.

TABLE II.—TEST RESULTS FOR PEM FUEL CELL AND ULTRACAPACITORS

Parameter	Configuration	Test conditions	Test results	Remarks
Transient test				
Voltage drop	fuel cell fuel cell and 20-capacitor bank	3 to 30 A	–21.99% –5.50%	System voltage 1 s after current transient
Voltage drop	fuel cell fuel cell and 20-capacitor bank	3 to 50 A	–36.97% –7.28%	System voltage 1 s after current transient
Discharge test				
Discharge time	20-capacitor bank	1- Ω load	4.7 min	Precharged to 43 V, discharge to 5 V
Discharge time	110-capacitor bank	10- Ω load	17.9 min	Precharged to 275 V, discharge to 5 V
Self-discharge test				
24-hr voltage drop	110-capacitor bank	No load	21.43 V (–7.8%)	Precharged to 275 V
Balance test				
Average voltage	110-capacitor bank	Precharged to 275 V	2.506 Vdc	
Minimum voltage			2.408 Vdc	
Maximum voltage			2.638 Vdc	

Concluding Remarks

The Ballard Nexa proton exchange membrane (PEM) fuel cell has been tested very successfully with symmetric ultracapacitor energy storage. The primary focus of this report is to present the test results of a symmetric ultracapacitor energy storage system. Neither the fuel cell nor the energy storage system exhibited any problems under the rigorous test conditions it was exposed to. The performance of the fuel cell and the ultracapacitor bank proved to be excellent. In addition, a bank of ultracapacitors was assembled and tested at 275 V, which is the nominal voltage rating of the Next Generation Launch Technology (NGLT) power system. The performance of the 275-V ultracapacitor bank was excellent, and there were no failures.

The transient responses of the power system were very revealing. With a 30-A step change in current, the fuel cell had a poor voltage regulation with a 7.4-V change in system voltage in 1 s without the capacitors. With the ultracapacitors the voltage regulation was excellent with a 2-V change in system voltage in 1 s. With a 50-A step change, the effectiveness of the ultracapacitors was more obvious. The

system voltage dropped 36.97 percent from 36.25 to 22.85 V in 1 s without ultracapacitors. The minimum system voltage with a 50-A step change and no ultracapacitors was 17.05 V, before the system could recover. The fuel cell was only able to supply 50 A for 2 s, and then the fuel cell shut down. The maximum current that the fuel cell can supply continuously without ultracapacitors is 35 A. With the addition of ultracapacitors, the system voltage dropped 7.28 percent from 35.68 to 33.08 V in 1 s with a 50-A step change. The system easily provided the 50 A of current called for on a continual basis.

PEM fuel cells have a rather fragile membrane with limited life. The life is significantly reduced by high stresses produced by large transient loads. The load must be minimized to prevent fuel cell damage, or an energy storage system is strongly encouraged if high peak loads exist. Ultracapacitors can easily handle large transient loads on a continual basis, and still provide a very long life, as no chemical reactions are occurring.

A bank of 110 ultracapacitors was assembled with a nominal voltage rating of 275 V to match the nominal voltage of the NGLT power system. The ultracapacitors were connected in a fashion to minimize interconnection impedance. The bank of ultracapacitors balanced extremely well with an average voltage of 2.506 V, a minimum voltage of 2.408 V, and a maximum voltage of 2.638 V. The bank of ultracapacitors was charged and discharged many times with no failures.

The high energy density of the PEM fuel cell is an excellent match with the high power density of ultracapacitors. The two devices complement each other to produce a power system which provides high energy density and high power density, while providing excellent system life.

Appendix A

Equipment Under Test

1.0 Ballard Nexa proton exchange membrane (PEM) fuel cell power module

1.1 Rated net power	1200 W
1.2 Rated current	46 A
1.3 Voltage range, dc	22 to 50 V
1.4 Operating lifetime	500 h
1.5 Fuel composition	99.99 percent dry gaseous hydrogen
1.6 Fuel supply pressure	69 to 1724 kPA (10 to 250 psig)
1.7 Fuel consumption	≤18.5 SLPM
1.8 Operating ambient temperature	3 to 30 °C (37 to 86 °F)
1.9 Relative humidity	0 to 95 percent
1.10 Location	Indoors and outdoors
1.11 Length by width by height	56 by 25 by 33 cm (22 by 10 by 13 in.)
1.12 Weight	13 kg (29 lb)
1.13 Certification	CSA, UL
1.14 Liquid water emissions	0.87 L (30 fluid oz.) maximum per hour
1.15 Noise emissions	≤72 dBA at 1 m
1.16 Fuel interface	45° flared fitting for 1/4-in. od tubing
1.17 Electrical power interface	#8 AWG electrical wire
1.18 Control interface	Full duplex RS 485

2.0 Maxwell BCAP0010 ultracapacitor

2.1 Configuration	Symmetric, dual layer
2.2 Capacitance	2600 F
2.3 Energy rating	8.125 kJ
2.4 Voltage rating	2.5 V continuous, 2.8 V peak each
2.5 Maximum series resistance	0.7 mΩ
2.6 Specific power density	4.3 kW/kg
2.7 Maximum current	600 A
2.8 Leakage current	5 mA
2.9 Operating temperature	−40 to 65 °C (−40 to 149 °F)
2.10 Storage temperature	−40 to 70 °C (−40 to 158 °F)
2.11 Dimensions	60 by 172 mm (2.36 by 6.77 in.)
2.12 Weight	525 g (1.16 lb)
2.13 Volume	0.42 L (25.63 in ³)

3.0 20-ultracapacitor bank (Maxwell BCAP0010)

3.1 Configuration	20 series ultracapacitors
3.2 Capacitance	130 F
3.3 Energy rating	162.5 kJ
3.4 Voltage rating	50 V continuous, 56 V peak
3.5 Maximum series resistance	14 mΩ
3.6 Weight	10.5 kg (23.15 lb)
3.7 Volume	8.4 L (512.60 in ³)

4.0 110-ultracapacitor bank (Maxwell BCAP0010)

4.1 Configuration	110 series ultracapacitors
4.2 Capacitance	23.64 F
4.3 Energy rating	893.89 kJ
4.4 Voltage rating	275 V continuous, 308 V peak
4.5 Maximum series resistance	77 m Ω
4.6 Weight	57.75 kg (127.32 lb)
4.7 Volume	46.2 L (2819.30 in ³)

Appendix B

Instrumentation System

A block diagram of the instrumentation system is shown in figure 5.

All fuel cell data were obtained by the fuel cell instrumentation system and transmitted to a personal computer (PC) via a serial interface. The PC logged the data. This data included the fuel cell voltage, the fuel cell current, and the fuel cell temperature. All other measurements were obtained with an Agilent model 34970A (Agilent Technologies, Inc., Palo Alto, CA) data acquisition system. It is a high-performance, microprocessor-controlled portable data acquisition system. It consists of a half-rack mainframe with an internal 6 1/2-digit (22-bit) digital multimeter. Three module slots are built into the rear of the unit to accept a combination of switch and control modules. Tests documented in this report were conducted with the digital data acquisition system programmed to meet the test matrix requirements. Type K thermocouples were used for all temperature measurements. Hall effect transducers were used for all current measurements. These data were transmitted to a PC via a serial interface. The PC logged the data.

A Dynaload WCL488 (TDI-Transistor Devices, Inc., Franklin, MA) 400-V, 12-kW load bank was used for all load tests. A Xantrex XFR (Xantrex Technology, Inc., Vancouver, BC, Canada) 300-V, 4-A power supply was used to precharge the ultracapacitors when necessary.

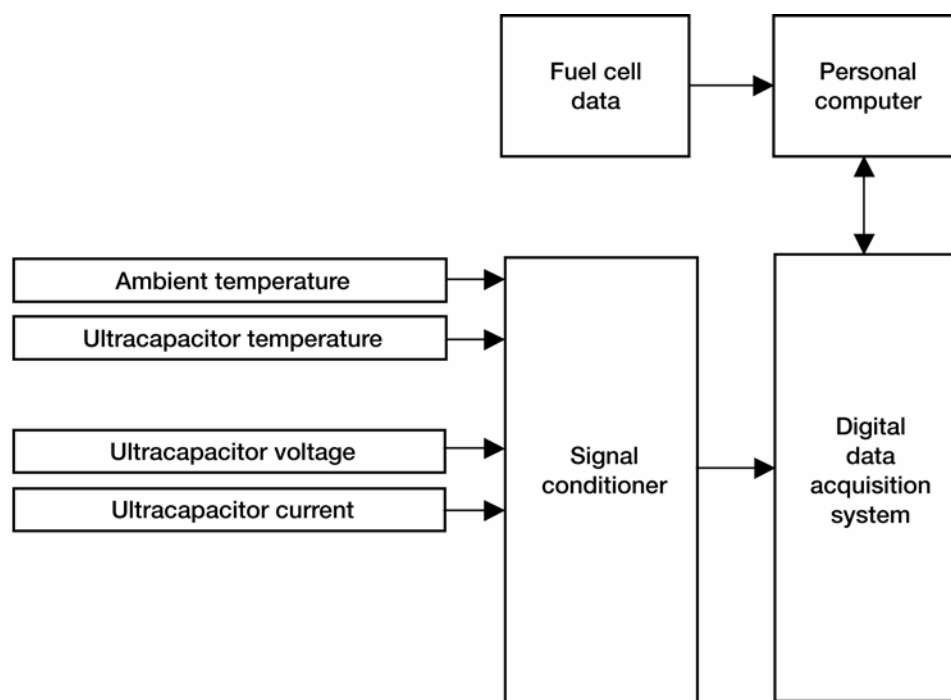


Figure 5.—Instrumentation system.

Appendix C

System Performance Test Results

A complete set of plots of the test results are included here. Table I identifies the tests that were conducted.

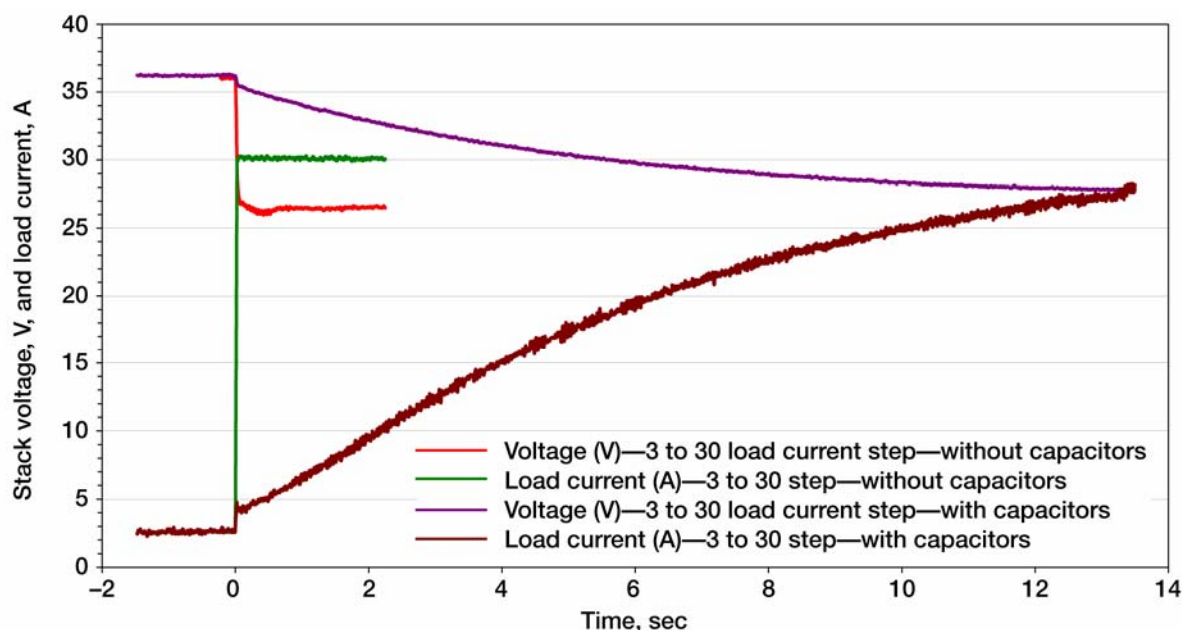


Figure 6.—PEM fuel cell transient test, 3 to 30 A step change (serial number: 00662).

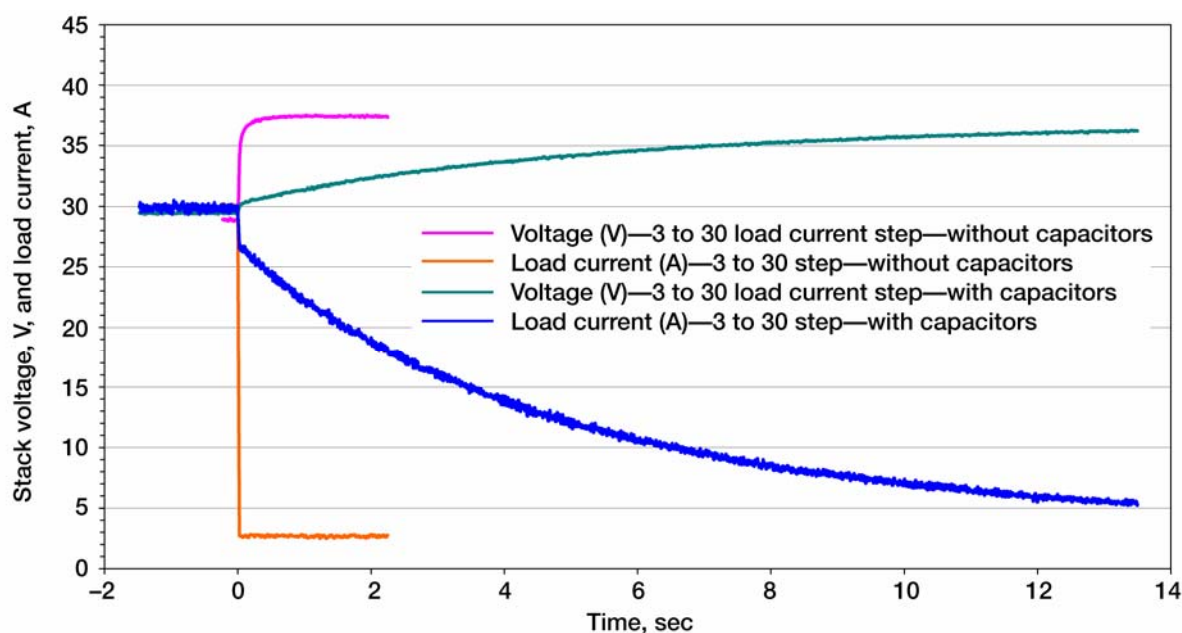


Figure 7.—PEM fuel cell transient test, 30 to 3 A step change (serial number: 00662).

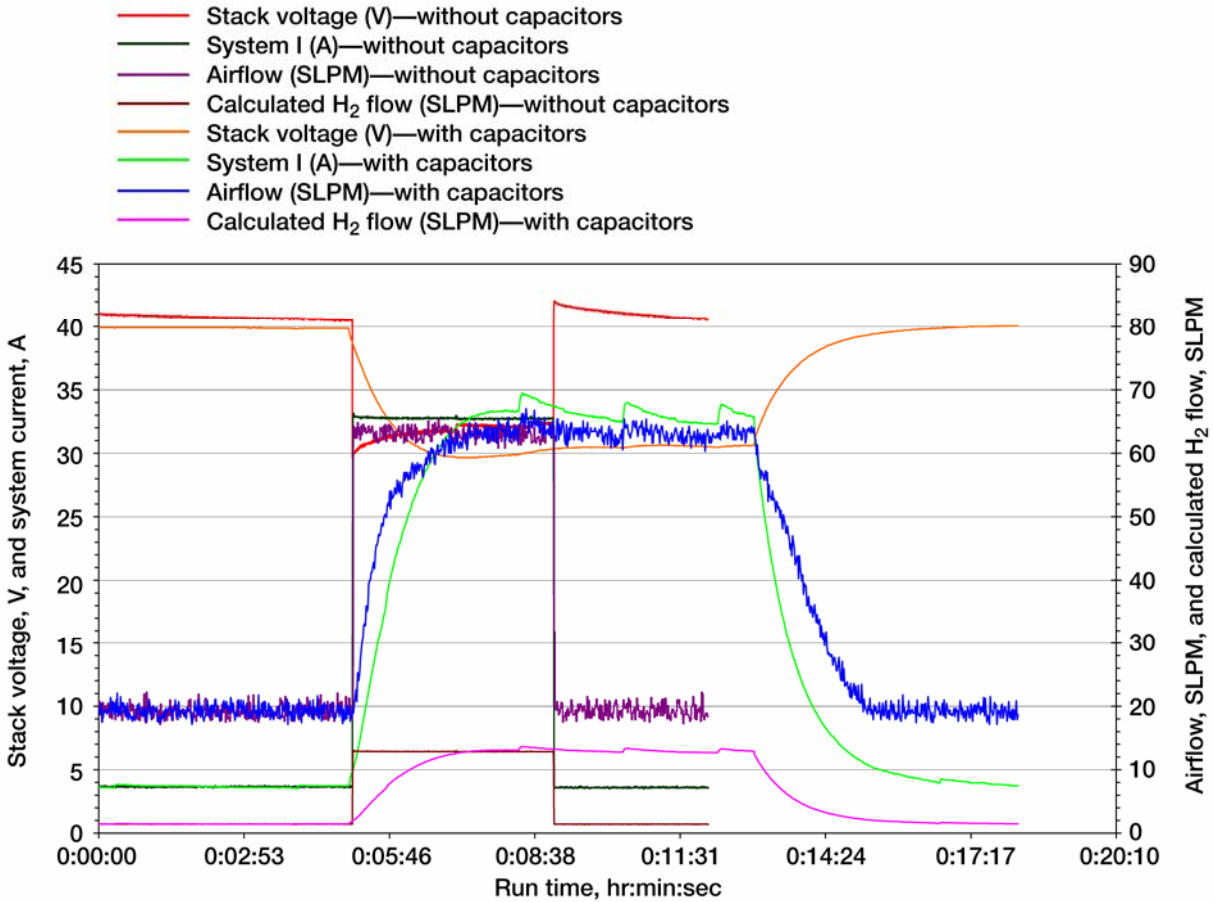


Figure 8.—PEM fuel cell transient test, 3 to 30 to 3 A load step (serial number: 00662).

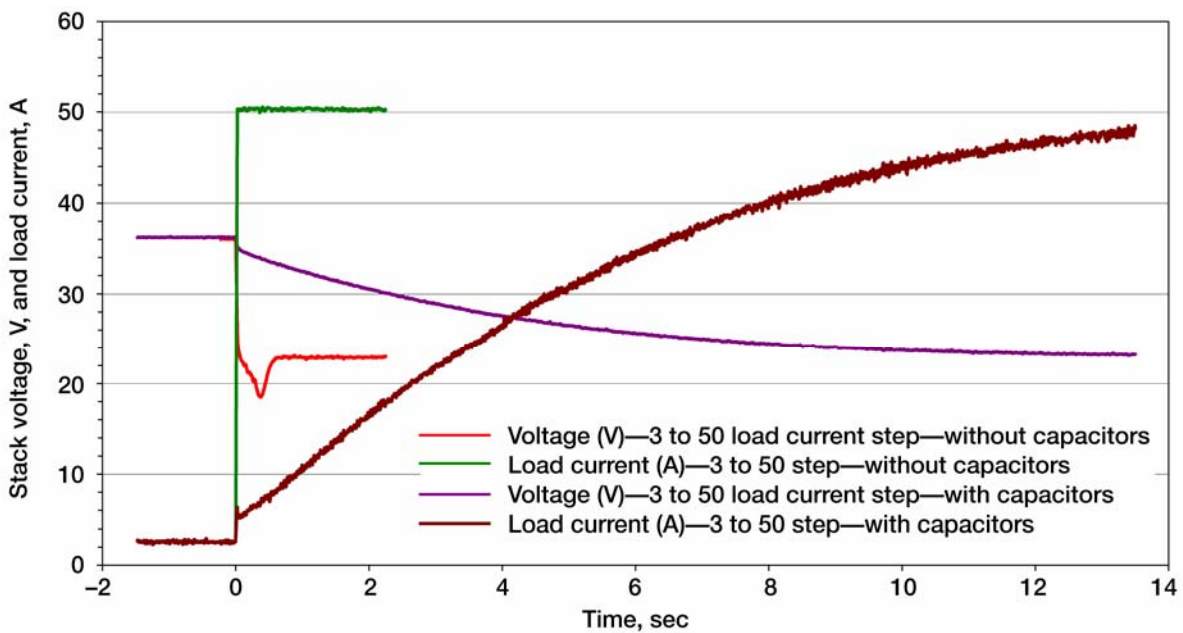


Figure 9.—PEM fuel cell transient test, 3 to 50 A step change (serial number: 00662).

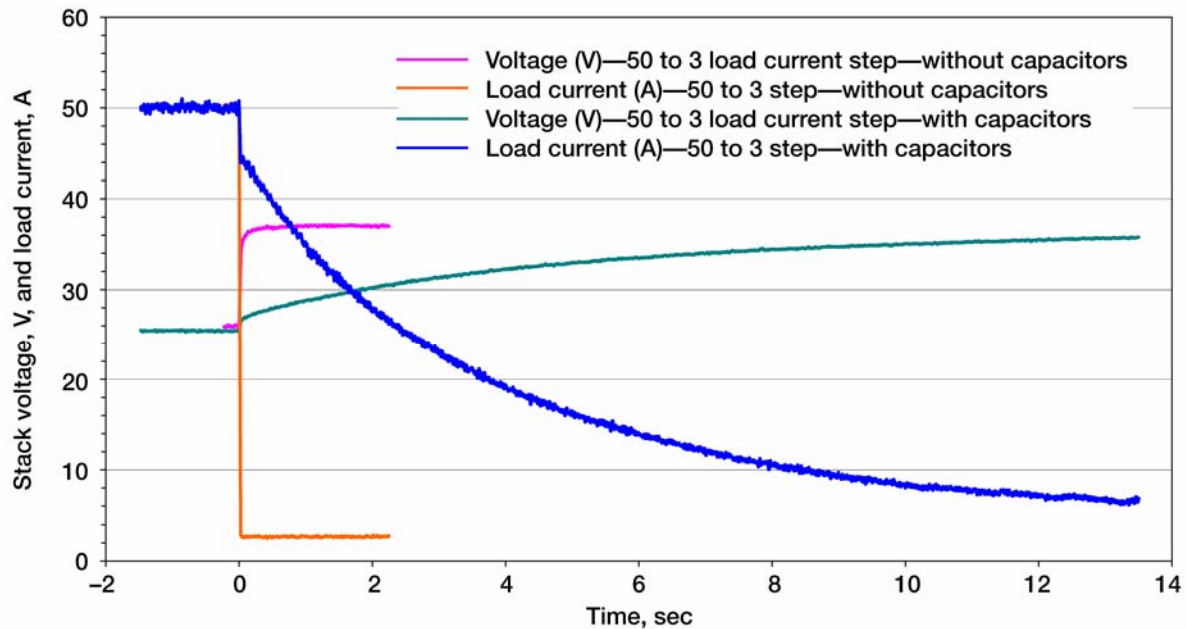


Figure 10.—PEM fuel cell transient test, 50 to 3 A step change (serial number: 00662).

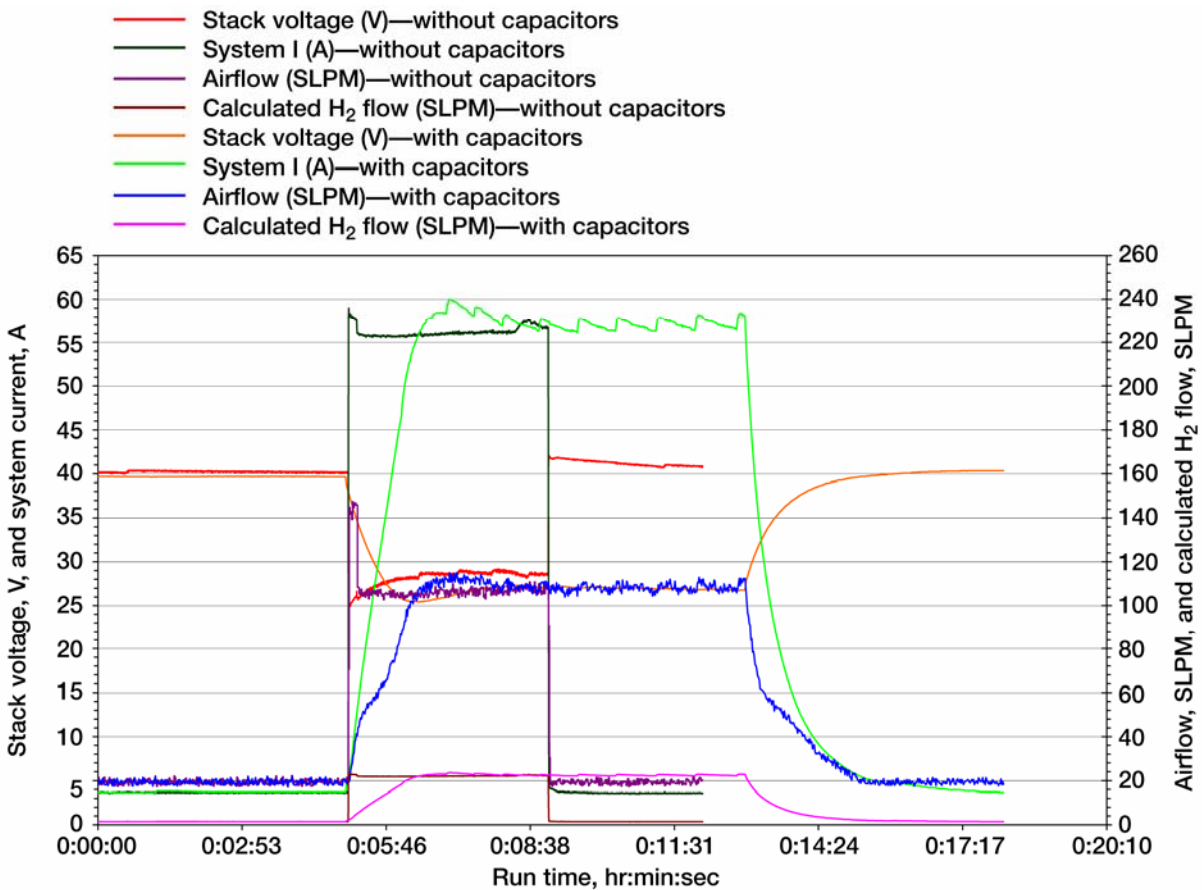


Figure 11.—PEM fuel cell transient test, 3 to 50 to 3 A load step (serial number: 00662).

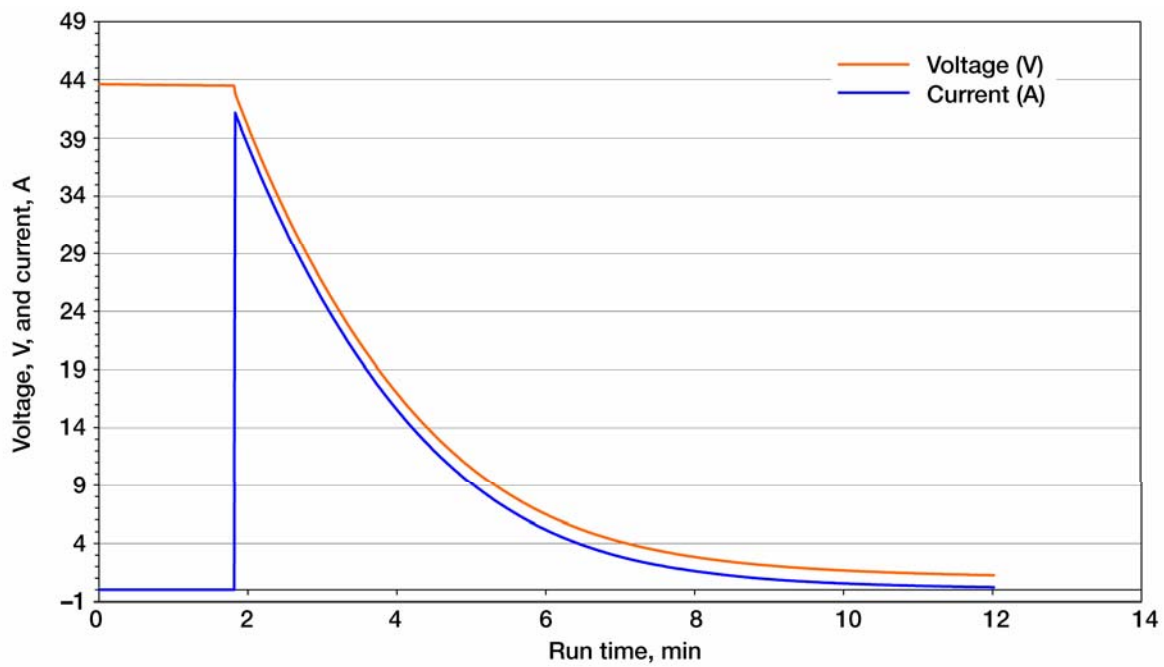


Figure 12.—Complete discharge test of 20-ultracapacitor bank. Fixed resistance discharge at 1 Ω load.

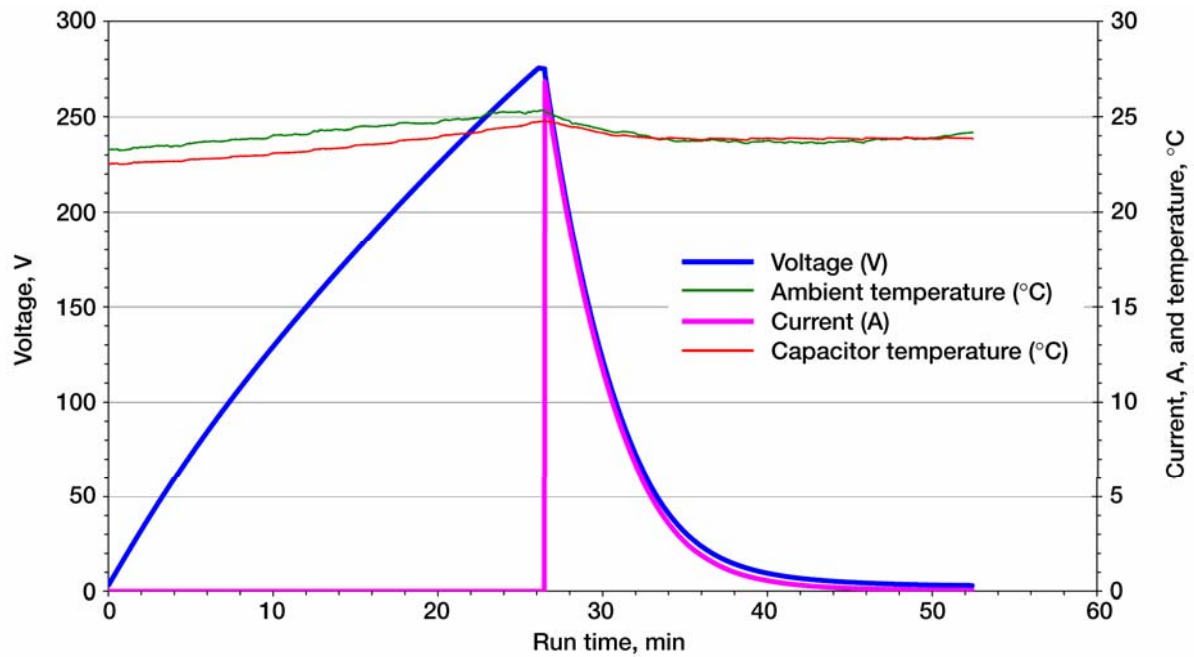


Figure 13.—Complete discharge test of 100-ultracapacitor bank. Fixed resistance discharge at 10 Ω load.

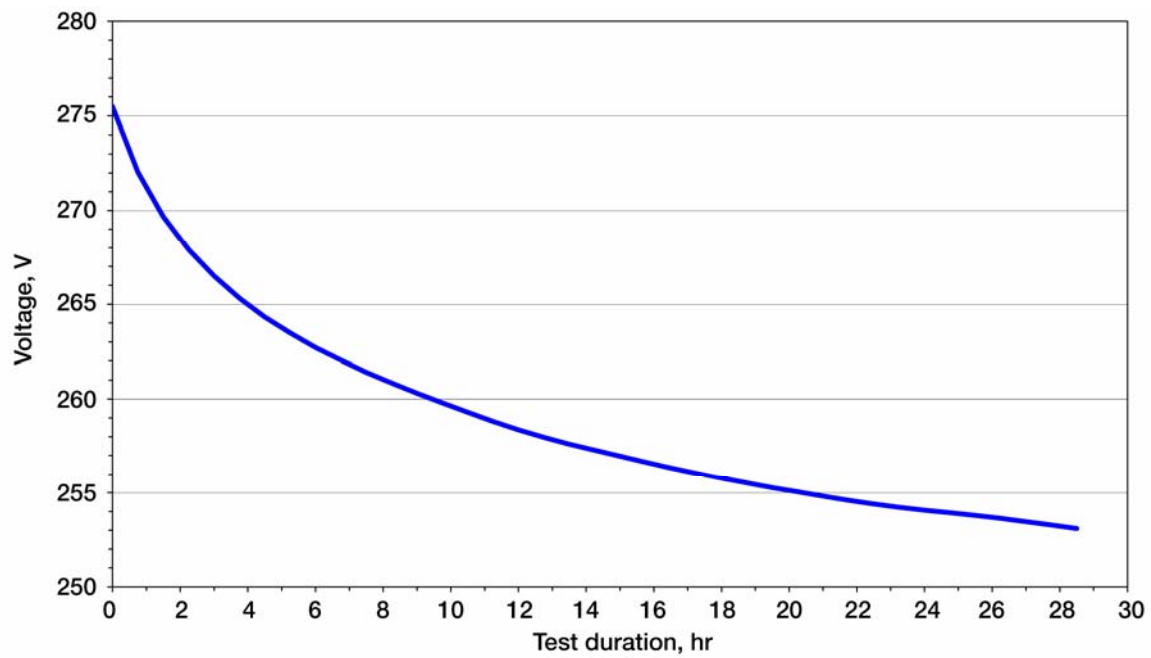


Figure 14.—Self-discharge test of 100-ultracapacitor bank after initial precharge to 275 V.

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13. ABSTRACT (Maximum 200 words) The NASA John H. Glenn Research Center initiated baseline testing of ultracapacitors for the Next Generation Launch Transportation (NGLT) project to obtain empirical data for determining the feasibility of using ultracapacitors for the project. There are large transient loads associated with NGLT that require either a very large primary energy source or an energy storage system. The primary power source used for these tests is a proton exchange membrane (PEM) fuel cell. The energy storage system can consist of devices such as batteries, flywheels, or ultracapacitors. Ultracapacitors were used for these tests. Ultracapacitors are ideal for applications such as NGLT where long life, maintenance-free operation, and excellent low-temperature performance is essential. State-of-the-art symmetric ultracapacitors were used for these tests. The ultracapacitors were interconnected in an innovative configuration to minimize interconnection impedance. PEM fuel cells provide excellent energy density, but not good power density. Ultracapacitors provide excellent power density, but not good energy density. The combination of PEM fuel cells and ultracapacitors provides a power source with excellent energy density and power density. The life of PEM fuel cells is shortened significantly by large transient loads. Ultracapacitors used in conjunction with PEM fuel cells reduce the transient loads applied to the fuel cell, and thus appreciably improves its life. PEM fuel cells were tested with and without ultracapacitors, to determine the benefits of ultracapacitors. The report concludes that the implementation of symmetric ultracapacitors in the NGLT power system can provide significant improvements in power system performance and reliability.				
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